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This report summarizes the Phase I STTR effort F49620-95-C-0069 from August 15, 1995 to August 14, 1996. The first section motivates the unique capabilities afforded by polarization imagers and the second section discusses the need and design for the next generation of polarization imager technology along with the critical advantages of this new technology. The third section discusses the technical hurdles needed to be transcended to make this new technology a reality. The fourth section describes the feasibility objective for Phase I and the corresponding actual results. The fifth section describes some of the low-level technical development details, and section six is a brief conclusion.

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FINAL TECHNICAL REPORT

PHASE I STTR: POLARIZATION IMAGER TECHNOLOGY

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0. ABSTRACT

This report summarizes the Phase I STTR effort F49620-95-C-0069 from August 15, 1995 -to- August 14, 1996. The first section motivates the unique capabilities afforded by polarization imagers and the second section discusses the need and design for the next generation of polarization imager technology along with the critical advantages of this new technology. The third section discusses the technical hurdles needed to be transcended to make this new technology a reality. The fourth section describes the feasibility objective for Phase I and the corresponding actual results. The fifth section describes some of the low-level technical development details, and section six is a brief conclusion.

1. MOTIVATION: WHY POLARIZATION IMAGERS ?

Polarization is a characteristic of light physically orthogonal to wavelength (i.e., "color") and intensity (i.e., "brightness"). Polarization carries a significant amount of additional information and therefore if sensed can provide a richer description of an imaged scene. Metaphorically, humans and video cameras are ``color blind" with respect to the perception of polarization -- Polarization Vision is a sensory augmentation that significantly generalizes both automated Image Understanding and able to improve human visual performance. Figure 1 illustrates this physical augmentation. The top of Figure 1 shows the electric field distribution of partially linear polarized light viewed head-on. This distribution is the superposition of an *unpolarized* compo-

nent consisting of an isotropic electric field distribution, with a *linear polarized* component consisting of an electric field oriented along a single axis. The human eye and video cameras only sense the energy magnitude of this distribution as "intensity". What is not visually perceived by humans and video cameras are the relative magnitudes of unpolarized and linear polarized components that constitute the light, nor the orientation of the axis of linear polarization if there is such a non-zero component. The relative proportion of linear polarization will be termed the *partial polarization* varying between 0 (completely unpolarized light) and 1 (completely linearly polarized light). The orientation of the linear polarization axis, if it exists, will be termed simply the *orientation* of polarization. Note that the orientation varies within the range $0 - 180^o$. Together the parameters (i) intensity, (ii) partial polarization, and, (iii) orientation, completely determine the state of partial linear polarization.

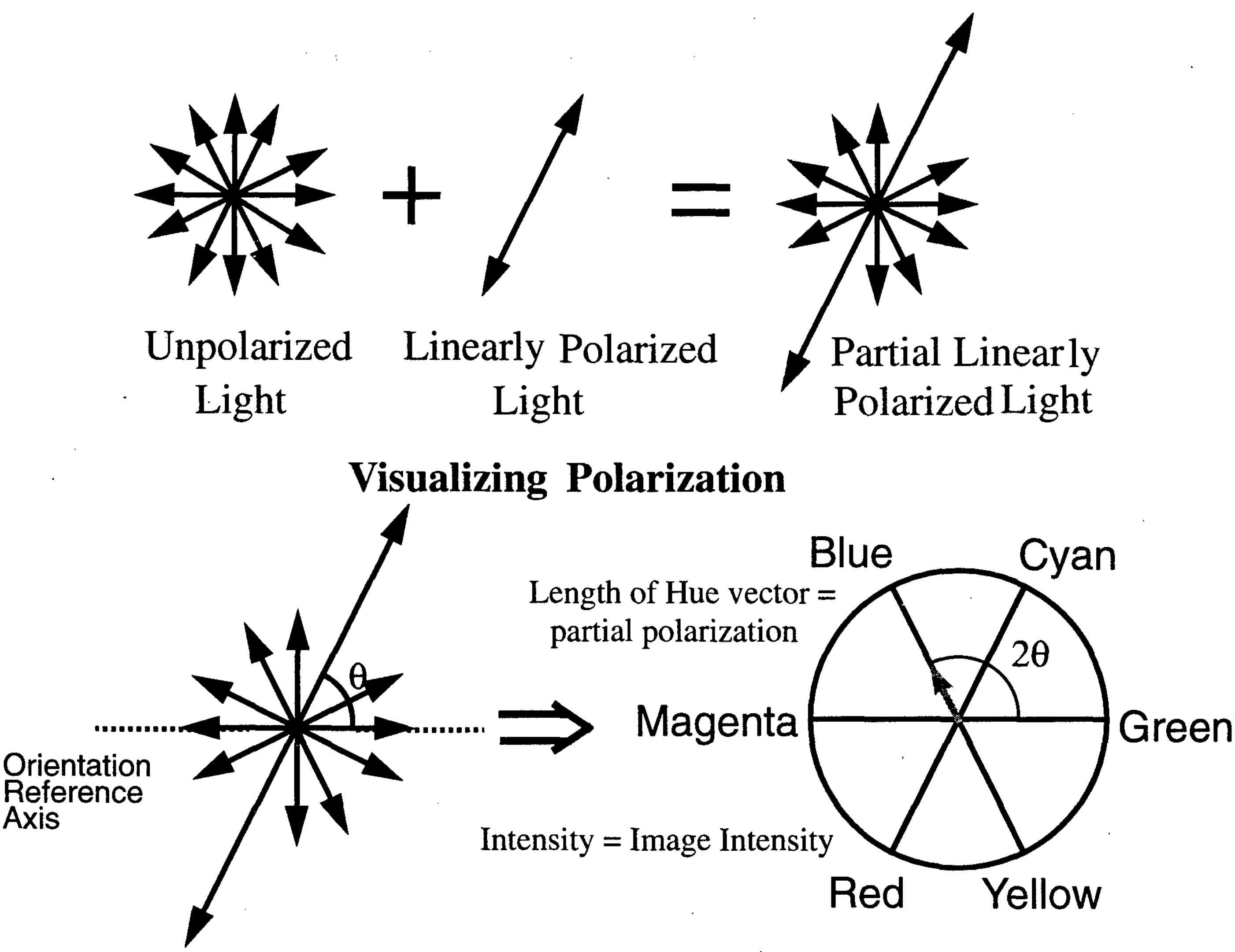


FIGURE 1

A state of partial linear polarization can be measured by resolving the electric field distribution along different orientation axes (e.g., with a polarizing filter). Resolving image irradiance at three (3) unique orientations is sufficient for unique measurement. Using an orientation reference and resolving the electric field at relative 0^o, 45^o, 90^o, if the image irradiances obtained at each pixel are respectively I_0, I_{45}, I_{90}, then:

$$\textbf{Orientation} \quad \theta = \frac{1}{2}\operatorname{atan}\frac{I_0 + I_{90} - 2I_{45}}{I_{90} - I_0}$$

$$\text{if } (I_{90} < I_0) \ [\text{if } (I_{45} < I_0) \quad \theta = \theta + 90 \text{ else } \theta = \theta - 90 \,]$$

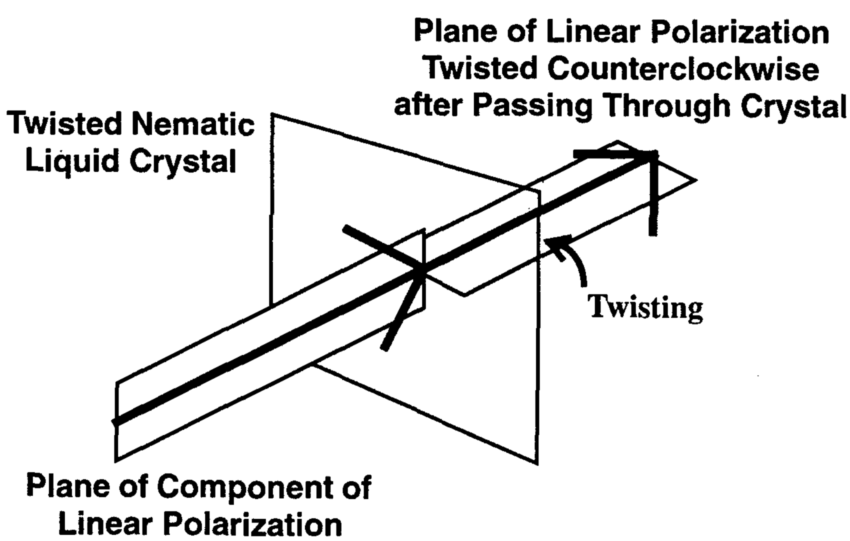
$$\textbf{Partial Polarization} = \frac{I_{90} - I_0}{(I_{90} + I_0)\cos 2\theta}$$

$$\textbf{Intensity} = I_0 + I_{90}$$

The bottom of Figure 1 shows a visual false color representation scheme for partial linear polarization mapping this into hue-saturation-intensity, originally proposed in [4]. This is one possible natural output of a fully automatic polarization imager. Orientation of polarization and partial polarization which are not observed by human vision are represented respectively in terms of hue and saturation. Since orientation of polarization is in the range $0 - 180^o$, orientation angle is multiplied by two to compute its hue representation. Chromaticity at a pixel in a polarization image means that there is some presence of linear polarization as saturation corresponds directly to partial polarization. Unpolarized light at a pixel in a polarization image is therefore achromatic. Intensity is of course simply intensity brightness in the image itself. This illustrates how *orientation* and *partial polarization* parameters of polarization are physically orthogonal to intensity augmenting visual perception.

The development of a general purpose polarization imager capable of accurate and rapid capture of polarization images in wide field of views over a broadband spectrum has a diversity of commercial applications, some of which are described below. Obtaining the measurement of partial

linear polarization by rotating a polarizing filter in front of a CCD camera is a mechanically active process that produces optical distortion and is difficult to fully automate for rapid polarization image acquisition. Unless the axis perpendicular to the polarizing filter is exactly aligned with the optic axis of the camera, small shifts in projection onto the image plane occur between different orientations of the polarizing filter. This motivated the development several years ago of a polarization camera design using two twisted nematic (TN) liquid crystals in series with a fixed polarizer modularly fitted onto the lens of a CCD camera. Nothing mechanically rotates; the polarizer remains fixed while the twisted nematic (TN) liquid crystals electro-optically rotate the plane of the linear polarized component of reflected partially linear polarized light in synchronization with the video rate of the camera. See Figure 2. The unpolarized component is not effected. Each TN liquid crystal is binary in the sense that it either rotates the plane of linear polarization by fixed n degrees, $0^o < n \leq 90^o$, which is determined upon fabrication, and, 0^o (i.e., no twist). Two TN liquid crystals are used, one at $n = 45^o$, and the other at $n = 90^o$, to insure resolving polarization components at $0^o, 45^o, 90^0$ relative orientations.



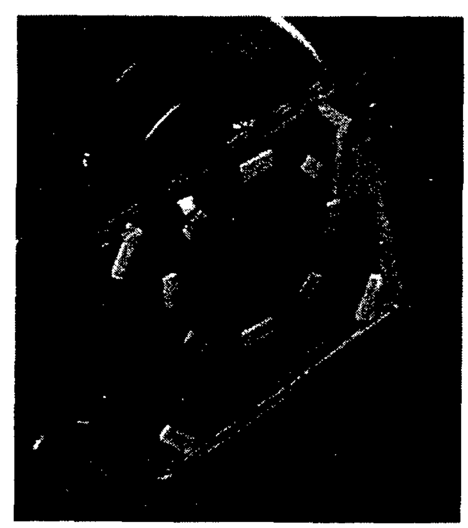


FIGURE 2

Polarization Cameras based upon serial acquisition of polarization component images using liquid crystals has been a low-cost and quick development solution for automatically obtaining

optically undistorted polarization images at arbitrary pixel resolution for outdoor and underwater scenes at up to 10Hz. Images taken with such cameras over the past few years have been instrumental in demonstrating the potential commercial value of future higher quality polarization imagers which amongst other capabilities can acquire polarization images in real-time. This STTR project proposes the building of such a high quality polarization imager with capabilities important to a number of commercial and military markets. The design for such "Second Generation" Polarization Imagers is explained in the next section.

One important application of polarization imagers is in providing unique capabilities for enhanced battlefield awareness in Automatic Target Detection/ Recognition systems. Orientation of polarization and partial polarization parameters of light being physically orthogonal to color and intensity are therefore immune to modified or degraded extrinsic ``appearance" of objects created by intensity and/or color camouflage, and, clutter. These polarization parameters are instead directly related to the intrinsic material composition, surface roughness, and, shape of objects [1], [2], [3]. This gives strong physical motivation for applying such a sensory modality towards the goal of detecting and recognizing man-made objects (e.g., military vehicles) that independent of extrinsic intensity and color appearance have material composition, surface properties and/or geometric properties that differ from surrounding terrain. Man-made objects having different shape characteristics and material parts (e.g., windows, viewing ports, headlight reflectors) can themselves be distinguished by various polarization signatures. This is demonstrated in Figures 3 thru 6. Figure 7 shows how visual contrast is enhanced for underwater mine detection. The false color representation in Figure 3, Figure 6, and Figure 7 is according to the scheme depicted in Figure 1. Color in Figure 4 and Figure 5 is simply a segmentation labeling. The left image of Figure 3 shows an intensity image of a HMMWV as viewed by an intensity video camera while the right image of Figure 3 shows a polarization image of the same scene. With pixels containing less than 5% linear polarization thresholded out to grey in the right image it is clear that the HMMWV stands out against background, except for the dirt road on which the vehicle stands. The amount of color saturation at a pixel in the left image is proportional to the percentage of linear polarization present (i.e., the partial polarization)- in this image the maximum partial polarization is 40%. The hue of the false color representing the orientation of the axis of linear polarization is physically related to the local surface orientation at each point on the vehicle [3].

Note for instance the large change in color hue as the roof curves into the right side of the HMMWV creating a very clear color edge -- such an edge feature is not evident in the intensity image and is one of a number of distinctive polarization signatures that can be used to augment recognition as well as augment detection capability under heavy occlusion should this local region be in line-of-sight. For this view of the HMMWV other polarization signatures include a three-way change in color hue at the rear trihedral corner, and, the blue color hue produced by the smooth glass windows against the red color hue of the painted (i.e., rough surface) right side of the vehicle. The left image in Figure 6 shows a polarization image of an M-60 tank which due to its 3-D shape complexity reveals a corresponding multitude of color hues, saturations, and, color edges. Such a structure has a wealth of polarization signatures not only from local shape characteristics but from a variety of viewing ports around the vehicle that have high partial polarization as high as 60% in some cases. Even under a number of heavy occlusion conditions polarization images have excellent potential for distinguishing a HMMWV from an M-60 using local signatures. Note the right image in Figure 6 which is a polarization image of a painted flat canvas decoy with a painted drawing of an M-60; although the color and intensity appearance across the canvas is that of an M-60, the intrinsic material composition and shape is uniform in turn producing a uniform polarization signature which can be easily distinguished from an actual vehicle. The left of Figure 4 shows an intensity image of a HMMWV under heavy occlusion (i.e., 80% occluded with only the roof in line-of-sight). The roof can be segmented by thresholding partial polarization at 30%, shown in orange in the right of Figure 4. The left of Figure 5 shows an intensity image of a HMMWV entirely draped with U.S. Woodland Net Camouflage and about 30% occluded by bush vegetation on the right of the vehicle. Thresholding of partial polarization at 30% reveals the camouflage netting distinct from other vegetation and scene elements. Polarization sensing provides an unprecedented capability for detecting camouflage nets which has been problematic for other sensors including FLIR, SAR, and LADAR.

Figure 7 shows a polarization image result obtained of an underwater mine 15 feet below water level (in a total of 80 foot depth seawater) using an underwater version of the polarization imager at the right of Figure 2, for the purposes of enhanced visual detection and recognition. The images were taken 15 miles off the coast south of Panama City in the Gulf of Mexico in an inert mine field controlled by the U.S. Navy. The images were taken by Navy divers. The left of Figure 7

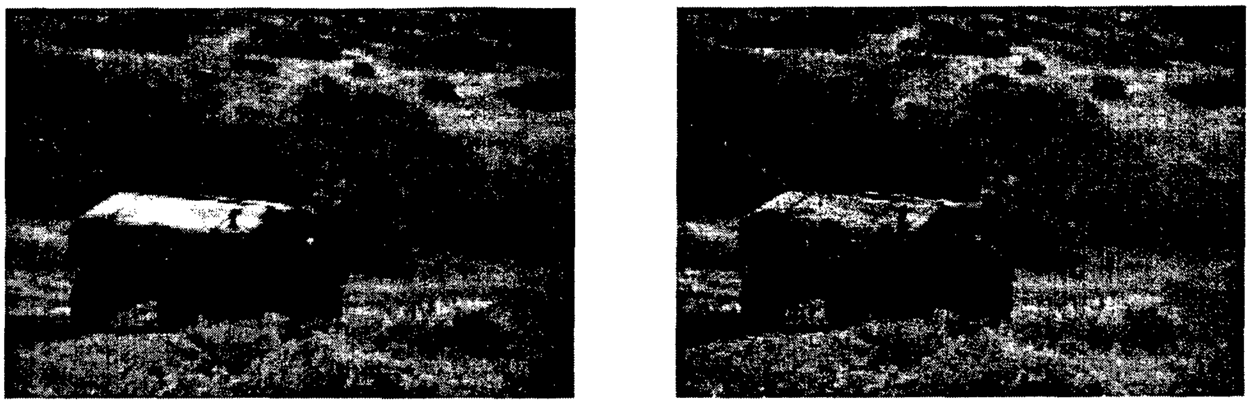


Figure 3: Intensity image (left) and polarization image (right) of a HMMWV.

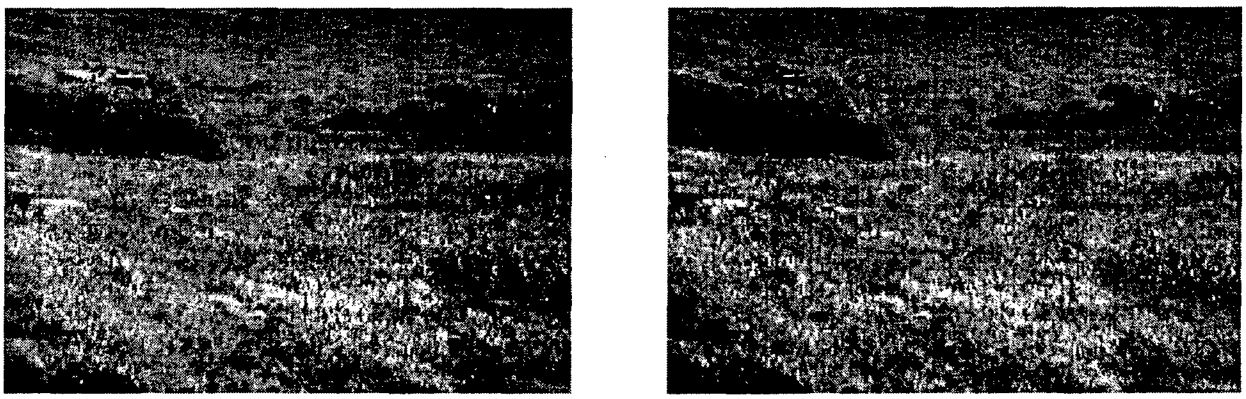


Figure 4: Intensity image (left) and thresholded polarization image (right) of a HMMWV heavily occluded by vegetation.

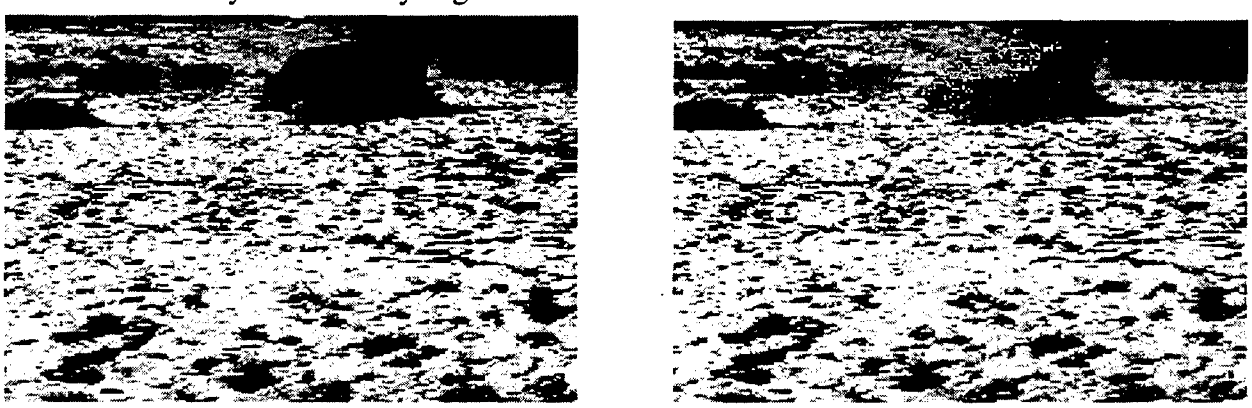


Figure 5: Intensity image (left) and thresholded polarization image (right) of a HMMWV partly occluded by vegetation and covered by Woodland Camouflage,.

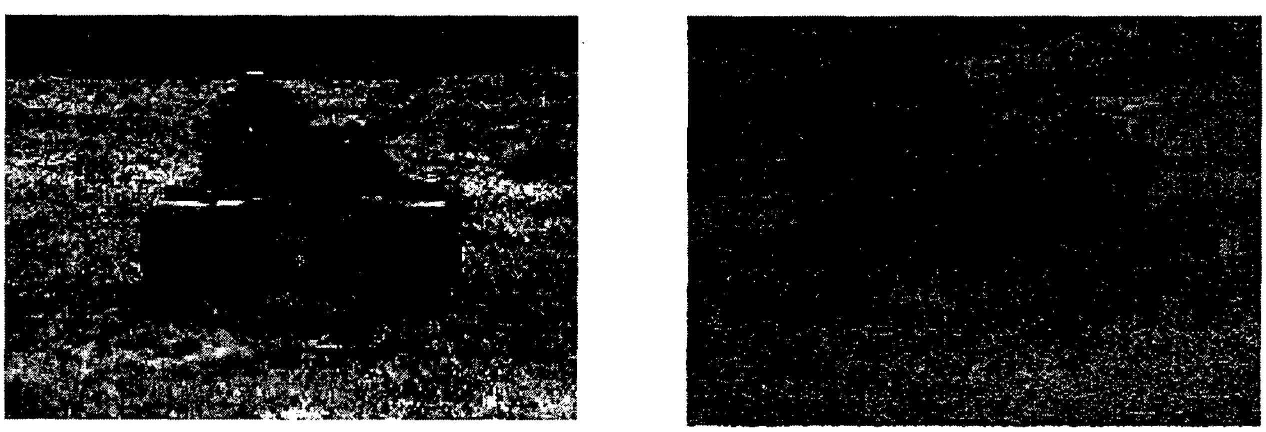


Figure 6: Polarization image of an actual M60 tank (left) and polarization image of an M60 decoy painted on canvas (right).

shows an intensity image of the spherical mine. The right of Figure 7 shows a "thresholded" polarization image using the mapping scheme in Figure 1 (the orange color hue in this case represents a linear polarization axis horizontal in the image). Yellow color hues are introduced from camera noise (this camera noise can be observed in the raw intensity image at the left of Figure 7) which can be eliminated with heavier shielded cables. In a completely noise-free polarization image the background of seawater should have a uniform color hue orange. By "thresholded" means that chromatic hue representing polarization is displayed at pixels in the right of Figure 7 if the degree of polarization is greater than or equal to 15%, and any degree of polarization at a pixel less than 15% is achromatic. The intensity of pixels where the degree of polarization is less than 15% is increased to highlight the region of interest, in this case the actual mine itself. Detailed analysis of the polarization image at the right of Figure 7 shows that the average degree of polarization at pixels on the mine is about 12% whereas the average degree of polarization at pixels on background seawater is significantly above 20% . A diver will be much more capable of visually detecting the underwater mine from the polarization image at the right of Figure 7 than from the standard intensity image shown at the left of Figure 7.

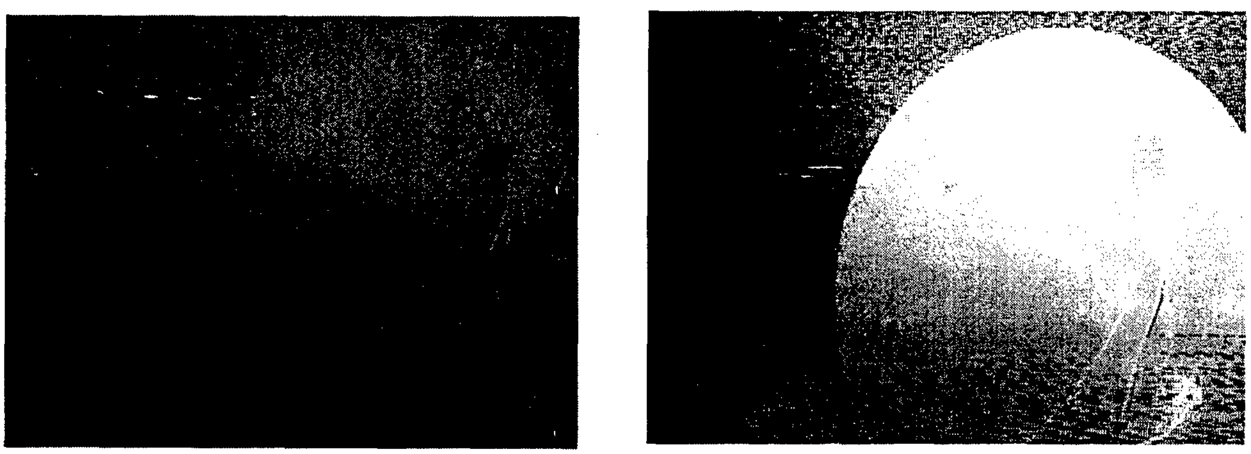


FIGURE 7

The examples in Figures 3 thru 7 clearly demonstrate unique capabilities not provided by existing technologies. From these examples it is clear that a system which simply visually displays measured polarization images-- either partial polarization, orientation of polarization, or, both simultaneously, is by itself a technology that significantly augments a soldier's visual capability for detection and recognition of man-made objects that could very well not be apparent using other sensors. Further augmentation of this technology with Image Understanding methods that are

either fully autonomous, or, semi-autonomous in allowing a user to interact with the processing of a polarization image, is anticipated to immensely further increase ATR/D performance. As a very simple illustration of just one interactive application, consider the examples of Figures 4 and 5: whereas man-made objects generally reflect more partial polarization than background the exact threshold amount will vary from scene to scene, as well as there may not be just one global threshold. A soldier will want the ability to dynamically raise/lower such a threshold on partial polarization either globally or in selected sub-image regions and see if certain characteristic shapes become readily visible.

This is but one example commercial market for polarization imagers. Other commercial markets, to be explained in more detail elsewhere, include Material inspection of circuit boards and semiconductor wafers, detecting defects on films and materials, detection and identification of corrosion, analysis of human tissue as an aid for medical diagnosis, analysis of tissue samples using polarization fluorescing dyes, polarization images and measurements for Remote Sensing, polarization measurements for Astronomers, Marine Biology where polarization vision is quite prevalent among underwater animals.

2. THE NEXT GENERATION OF POLARIZATION IMAGERS

While the design concept for liquid crystal based polarization imagers has been quite successful in demonstrating the capabilities of polarization vision, a number of limitations of this design severely restricts the commercial market potential as a general purpose polarization imager. The following summarizes two critical limitations of the liquid crystal design:

- Finite active switching time of liquid crystals restrict polarization component image capture to a minimum of 1/30 second, and therefore because the design is serial acquisition based, 3 polarization component images serially acquired implies a minimum of 1/10 second for complete polarization image capture. 10 Hz polarization image acquisition is well below acceptable 'real-time' rates for a number of commercial applications.

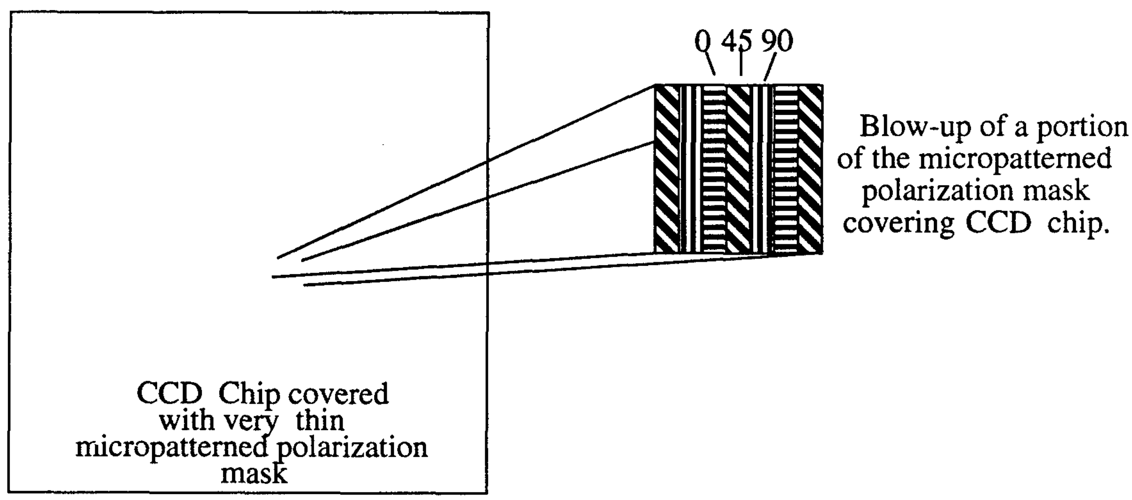
- The rotation of the linear polarized component by liquid crystal twisting, depicted in Figure 2, is wavelength dependent limiting accuracy of polarization measurement in broadband spectrum polarization measurement applications which eliminates a large commercial market. Typically a 45 degree twist (90 degree twist) liquid crystal cell centered at 550nm will rotate at only 43.5 degrees (88.5 degrees) at 400nm and 46.5 degrees (91.5 degrees) at 700nm. This technology is not likely to improve in the next decade as such liquid crystal rotations are sufficient for display technologies, and are not commonly used for broadband measurement technology.

As a result of the first limitation, polarization imaging of dynamic scenes and/or from moving platforms (e.g., imaging moving vehicles, imaging from an Unmanned Aerial Vehicle or a satellite, etc.) will appear "grainy" and color smeared. This will occur when scene elements translate in the image by more than a half-pixel over the course of the 1/10 second acquisition time: such movement creates brightness variations at the same pixel between adjacent polarization component images producing false measurement of polarization- hence the smearing of false color representation. For instance, the polarization image in Figure 7 had to be obtained the instant when the Navy diver was not moving relative to the tethered mine-- an unusual condition given the usual lateral and vertical bobbing from ocean currents. Due to only a 10Hz polarization image acquisition rate, 95% of the polarization images came out color smeared, and although polarization vision is excellent in enhancing visual contrast for underwater mine detection, this is severely degraded by the design limitation of the current polarization imager. It is estimated that at least a 30Hz polarization image acquisition rate would give consistently acceptable results.

The second limitation implies a significant restriction on the accuracy of broadband polarization measurement at a pixel. Laboratory experiments with liquid crystal polarization cameras sensing narrowband light shows a measurement accuracy to well within 1 degree of polarization orientation. However, polarization images outdoors with typical broadband 400-700nm conditions have shown as much as +-5 degree variations in polarization orientation measurement. Measurement of partial polarization in common broadband light conditions have shown as much as 5% variation. This is very significant for applications such as Automatic Target Detection and Recognition where quantitative polarization measurements are important for automatically recognizing distinctive polarization signatures (e.g., measurement of orientation of polarization being directly related to surface orientation is important for constraint determinations). This is to name only one of a multitude of reasons for measurement accuracy.

The proposed design for the "Second Generation" of polarization imagers transcends these limitations by fully integrating *passive* (distinct from *active*) polarization optics directly onto the CCD photosensing chip such that the three $0^o, 45^o, 90^o$ states are sensed simultaneously. Figure 8

shows such a design whereby a thin filmed patterned mask of passively polarizing material, periodically polarizing at orientations $0^o, 45^o, 90^o$ respectively at adjacent single columns of pixels, is deposited onto the CCD chip. The sensing rate of complete polarization images using this design is therefore limited only by the sensing rate of the CCD photochip itself and *not* by any operating characteristics of the polarization optics. While the complete polarization image acquired is at 1/3 the horizontal pixel resolution of the CCD photosensing chip, experienced practitioners with video cameras will immediately recognize that this is exactly analogous with color sensing using a single CCD chip color camera which uses Red, Green and Blue pixel column



Proposed "Second Generation" Polarization Imager with passive polarization optics integrated on CCD chip

FIGURE 8

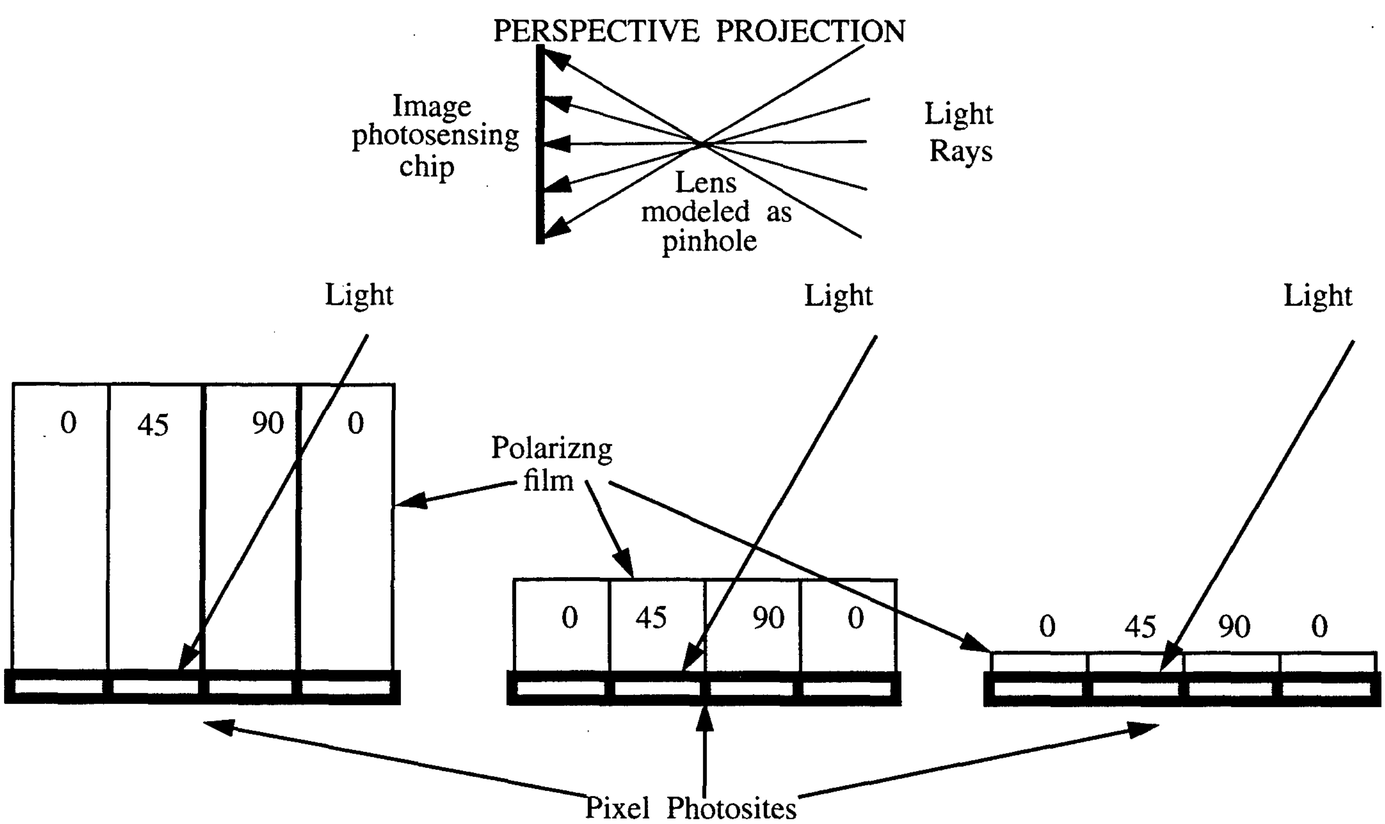
striping, respective to the $0^o, 45^o, 90^o$ states (e.g., almost all commercially available color CCD camcorders are built this way). Color sensing CCD chips typically have a high horizontal pixel resolution to compensate for this, and it is proposed that the polarization patterned mask be deposited on such a CCD chip. Unlike active materials that rotate states of polarization, passive materials that use dichroism can be made to polarize light independent of wavelength over large spectral bandwidths (e.g., 400-700nm) and have a wide acceptance angle over which polarization is efficient (e.g, typically up to 40 degrees angle relative to the surface normal of the polarizing material).

The following are additional advantages of this polarization imager design:

- Because the polarization optics is passive there are no additional power consumption requirements such as that required by electro-optics. Because the polarization patterned mask is extremely thin the weight added to a camera system is so small as to be trivial.

- The fully integrated photosensing chip design makes it completely transparent to the user in that the user can functionally operate the camera without being aware of any additional design features relative to an ordinary camera system.

The ability of a polarization imager to accurately measure a high resolution polarization image in a wide field of view using the design in Figure 8 imposes the condition that the thickness of the micropatterned polarization mask be as small as possible and at least as small as the width of a single pixel column on a photosensing chip. This is due to simple light ray geometry illustrated in Figure 9. The leftmost, center, and, rightmost illustrations at the bottom of Figure 9 shows the path



CROSS-SECTION VIEW ACROSS DIFFERENT PIXEL COLUMNS WITH DEPOSITED MICROPATTERNED POLARIZATION FILM OF DIFFERENT THICKNESSES

FIGURE 9

that a light ray takes relative to a photosensing chip on which polarizing film is deposited when the film is respectively 3.0, 1.0, and 0.25 pixel column widths. This is representative of photosite pixels near the edge of the image plane for a standard 30 degree conical perspective view shown at the top of Figure 9 (e.g., the view provided by a 25mm lens mounted in front of a 1 inch format imaging chip). If the thickness of the micropatterned polarization mask is 3.0 times the column pixel width, as shown in Figure 9, the path of a number of light rays incident on the pixel photosite at about 30 degrees to the image plane will partially pass through polarization material comprising three different states thereby contaminating the polarization component measurement- in fact all light incident on a pixel photosite at this angle will pass through at least two different states of polarization material. At 1.0 column pixel width film thickness, for 30 degrees incidence approximately one-half the entire pixel area will be contaminated by light passing through some combination of two adjacent polarization states. At 0.25 column pixel width film thickness this amount of contamination is reduced to 14% at the edge of the pixel photosite. Because the quantum efficiency of pixel photosites is generally much lower at the edges, further reduction in film thickness becomes unnecessary.

3. MAJOR TECHNICAL HURDLES

While the analogy is made between the columned micropatterned polarization mask on a CCD chip as illustrated in Figure 8, and, color striping on an RGB CCD chip, the technology for creating micropatterns with polarization material to the specifications required for a polarization imager is completely dissimilar. Before the beginning of this Phase I STTR project, the only existing technology using any kind of polarization patterning was for certain 3-D stereo displays which utilize an optical layer of alternating 0, 90 degree polarization orientation states. Besides not being generalizable to more than two polarization column states, the optical and physical characteristics of such materials are not even close to that required for a polarization imager. For instance the thickness of the material as well as the width for each of the 0, 90 degree polarization states are on the order of a few to several hundred microns. Compare this size with that of the size of typical pixel photosite widths on imaging chips which are on the order of 10-20 microns. For a sense of scale, observe again the leftmost illustration at the bottom of Figure 9 depicting a polarization film thickness three times the pixel photosite column width on an imaging chip, and which due to thickness is problematic for wide view polarization imaging- polarization material

used by 3-D stereo displays is an order of magnitude thicker. Also, the smallest width for one polarization column state on material used in 3-D stereo displays would span at least 10 pixel photosites.

Furthermore, the polarization efficiency of such material while sufficient for 'visual' display technology is not sufficient enough for quantitative measurement of polarization. A standard measure for the linear polarizing efficiency of a material is it's *extinction ratio* which is the ratio of the light transmitted through two pieces of the material with polarization axes parallel aligned, divided by the light transmitted through two pieces of the material with their polarization axes mutually perpendicular (i.e., crossed polarized). A micropatterned polarization mask for a polarization imager should have at least 100:1 extinction ratio which is uniform across the micropatterned array. This micropatterned array must be deposited on the photosensing chip such that the polarization state columns are precisely aligned over pixel photosite columns. Since there is typically extremely little to no space between adjacent pixel photosites on an imaging chip, this alignment must be done to sub-micron accuracy. The term *effective* extinction ratio, in relation to this project, refers to the sensed linear polarizing efficiency at a pixel after the micropatterned polarization mask has been deposited on the chip. The effective extinction ratio will be less than the extinction ratio of the mask due to some non-zero misalignment over the pixel, non-zero thickness of the mask along with nonflatness of the mask over the entire photosensing chip. The effective extinction ratio at a pixel can be measured by imaging a linear polarizer, dividing the sensed pixel grey value when the polarization axis of the linear polarizer is parallel to the polarization state covering the pixel, by the sensed pixel grey value when the linear polarizer is relative rotated by 90 degrees.

The following summarizes the major technical hurdles:

- **(I)** Reduce the thickness of micropatterned polarization material by two (2) orders of magnitude (i.e., from a scale of 300-500 microns to a scale of 3-5 microns, while achieving 100:1 polarization extinction ratio).

- **(II)** Increase the level of resolution detail for micropatterning on polarization material by over an order of magnitude (i.e., need to be able to produce polarization column states of width 10-20 microns down from prior capability before the Phase I STTR effort which was at about 300 microns).

- **(III)** The transition between polarization state columns must be "sharp" in that the linear polarizing orientation property should suddenly change across column borders, and the borders themselves should be straight (i.e., not 'jagged') to sub-micron level.

- **(IV)** The micropatterned polarization mask must be accurately aligned such that the mask polarization column states are precisely positioned over pixel photosite columns to submicron precision.

The result of transcending these major technological hurdles will in fact facilitate significant spin-offs to other application areas, as will be discussed in the STTR Phase II proposal. There are other technical hurdles which include incorporating the micropatterned polarization "chip" into a camera imaging system, and developing additional hardware to fit onto a digitizing card to support some unique modes of operation of a polarization imager along with development of associated software routines. These additional technical hurdles require more standard development issues

4. OBJECTIVE AND RESULTS FOR PHASE I

Direct quotation from SECTION C - DESCRIPTION/SPECS/WORK STATEMENT of the STTR contract states:

1. Demonstrate the feasibility of depositing a three state alternating micro-polarization pattern of optically polarizing columns of material on the order of 10 to 20 microns per column, onto a photo-sensing chip. Each column of a given polarizing orientation to be precisely and consistently aligned over a column of pixels on the photo-sensing chip.

2. Incorporate this photo sensing chip with deposited micro-polarization pattern into a video camera system and test the partial linear polarization measurement performance from imagery.

Altogether, this work statement supports an important aspect of the feasibility for each of the 4 major technical hurdles listed and discussed in section 3. For Phase I, the micropatterned polarization mask is produced separately and deposited by physically sliding the mask over a photochip using a probe attached to a nano-positioner capable of submicron incremental movement. For a micropatterned polarization mask with 100:1 extinction ratio and made to 5 micron thickness or less, it was originally expected at the beginning of Phase I that an effective extinction ratio of 10:1 by physical contact would be achieved; in fact on average over twice this extinction ratio

was achieved as explained below ! Given that the mask, which for Phase I is separate from the photochip, is not perfectly flat and that small perturbations in the mask 'lift' portions of the mask off the photochip, achieving an effective extinction ratio of 10:1 is an excellent feasibility demonstration. In Phase II it is proposed to extend the process of producing the mask directly onto the photochip so that the mask is adhered to the photochip surface (i.e., there is no air gap) which should achieve an effective extinction ratio very close to that of the mask itself.

In anticipation of eventual commercialization, it was decided to test feasibility of depositing a micropatterned polarization mask on a CCD photochip that would modularly fit into a high quality, relatively low-cost video camera system. A critical requirement not supported by popular NTSC video standard cameras is that there should be exact registration between a physical pixel photosite on the CCD imaging chip and the displayed image pixel. An image pixel displayed by an NTSC video camera system results from the sensing of fractions of at least two physical photosite pixels (e.g., typically the horizontal line image signal created from 770 physical photosites is sampled in 512 places) which clearly is problematic for the proposed design of a polarization imager. The choice of the camera systems used are the Electrim EDC-1000 series which are high quality low-cost video camera sensors supporting the desired exact registration property. EDC-1000 series cameras use high quality Texas Instruments CCD imaging chips which can be purchased separately, modified, and modularly fit into an electronic socket inside the Electrim camera. The Electrim EDC-1000 series cameras can be operated with almost any PC computer, and each camera comes with software that allows easy display on VGA monitor screens with capability of zooming onto pixel subregions of an image.

Figure 10 shows a piece of one of the earlier developed micropatterned polarization masks aligned on a CCD chip (about midway through the project year). The CCD photochip is a Texas Instruments TC211 which has been incorporated into an Electrim Model 1000 camera. Each pixel photosite on the TC211 chip is physically 16 microns wide by 13 microns vertical. The polarization column states on the micropatterned polarization mask in Figure 10 are 48 microns wide, therefore spanning 3 pixel photosites per column. The image in Figure 10 was taken with the Electrim Model 1000 camera using a linear polarizer placed in front of the lens, as shown in Figure 11 (note the nanopositioner to the right of the camera in this figure). For the image in Figure 10, the linear polarizer in front of the lens is oriented at horizontal 0 degrees relative to pixel scan-

lines. The light, middle grey, and dark light patterns result from varying amounts of cross-polarization of the linear polarizer with respect to the polarization column states on the micropatterned mask. Figure 12 illustrates the effect on transmitted light that is sensed at a pixel for different *relative* orientations

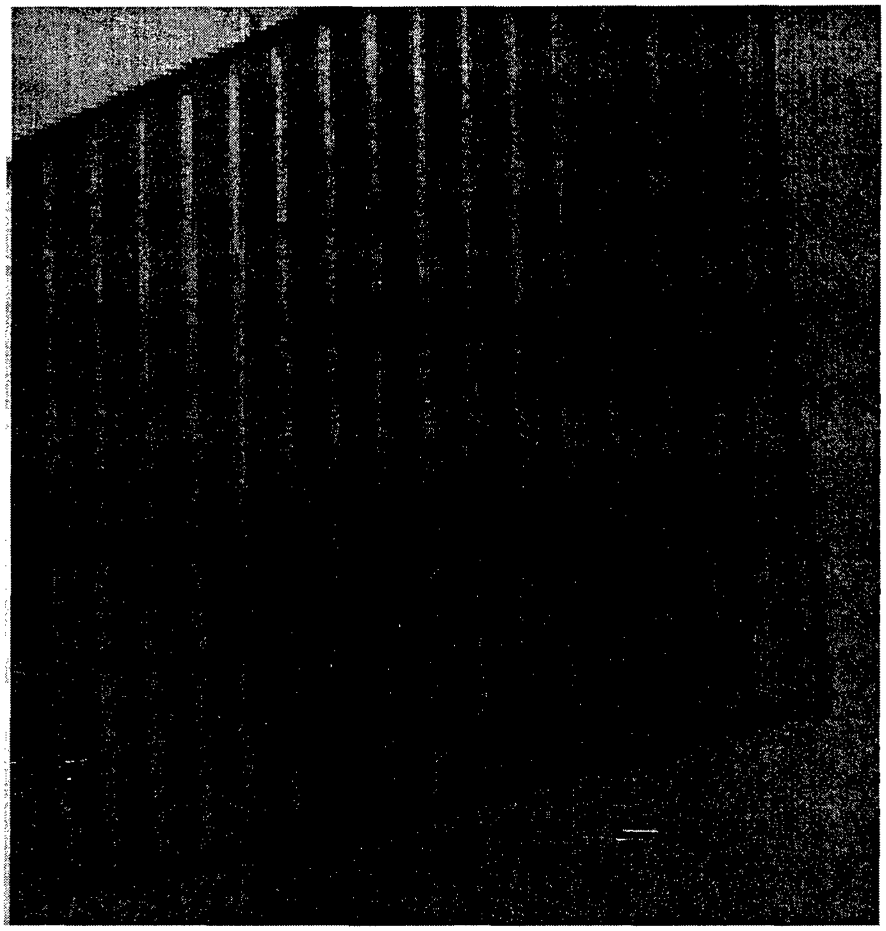


FIGURE 10

of two polarizers, in series, with transmission axes respectively at relative 0, 45, and, 90 degrees. Therefore, when the transmission axis of the linear polarizer shown in Figure 11 is oriented horizontally along pixel scanlines, the transmitted light illustrated at the left, center, and right in Figure 12 results respectively for polarization column states of 0, 45, and 90 degrees.

Figure 13 shows zoomed in portions of images for one of the recent micropatterned polarization masks having 16 micron (i.e., one pixel photosite column width size) deposited on the TC211 imaging chip. As described in more detail in Section 5 below, the thickness of this micropatterned polarization mask is just over 4 microns. Images (a), (b), (c), and, (d) in Figure 13 were taken with the linear polarizer shown in Figure 11 respectively oriented at 0, 45, 90, and 135 degrees

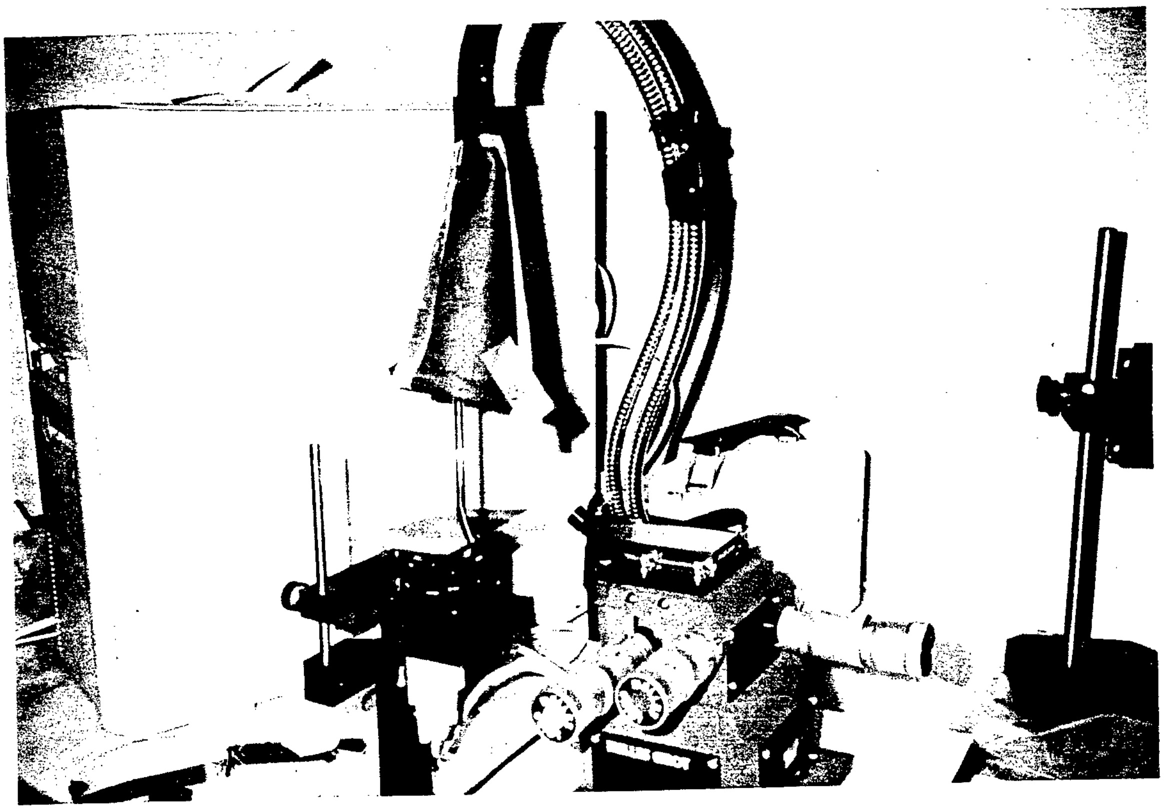


FIGURE 11

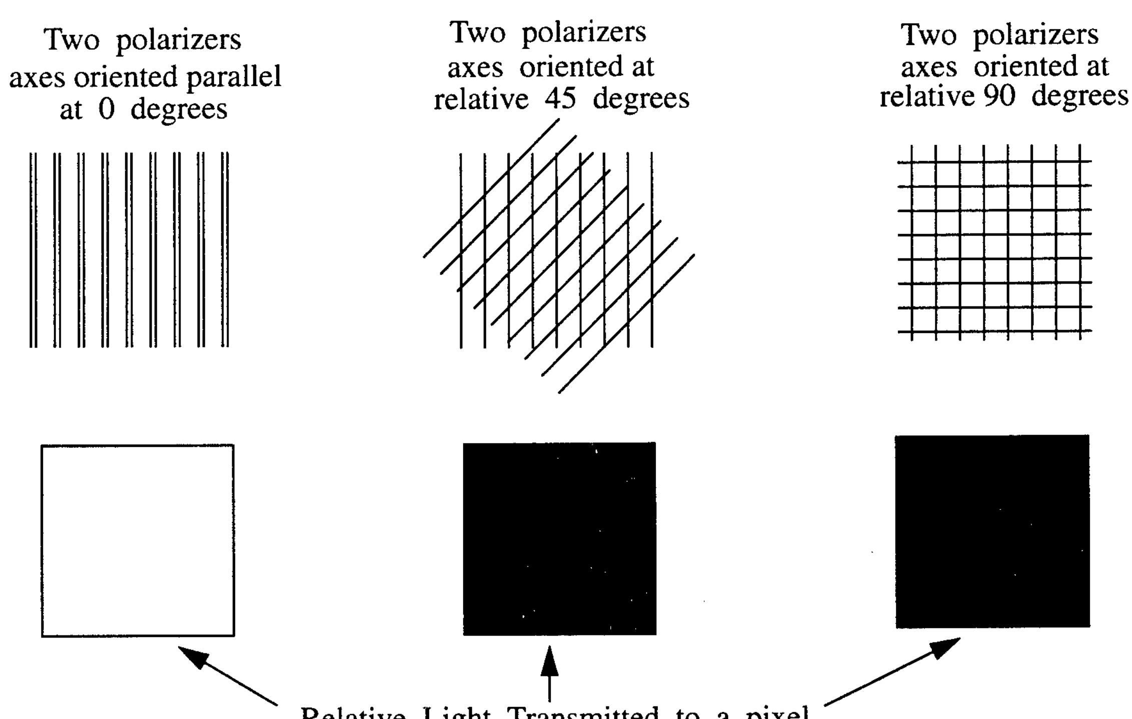
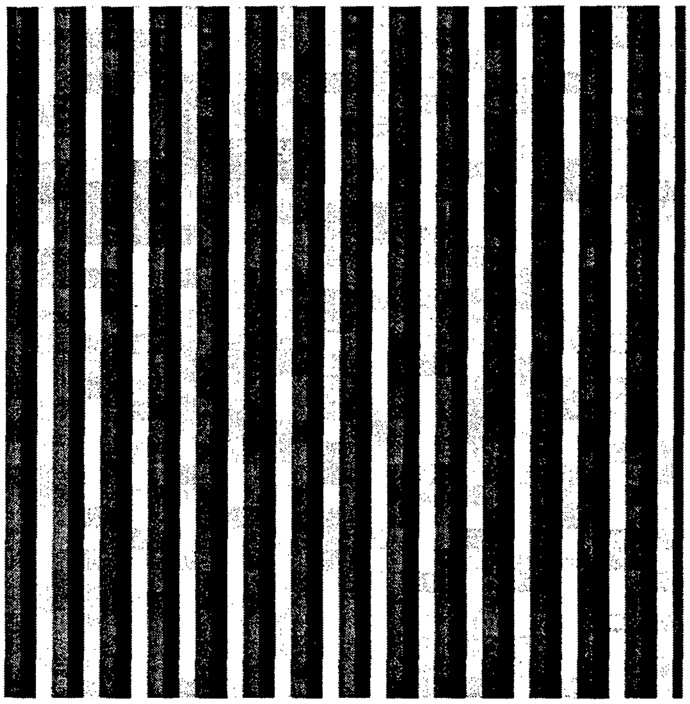
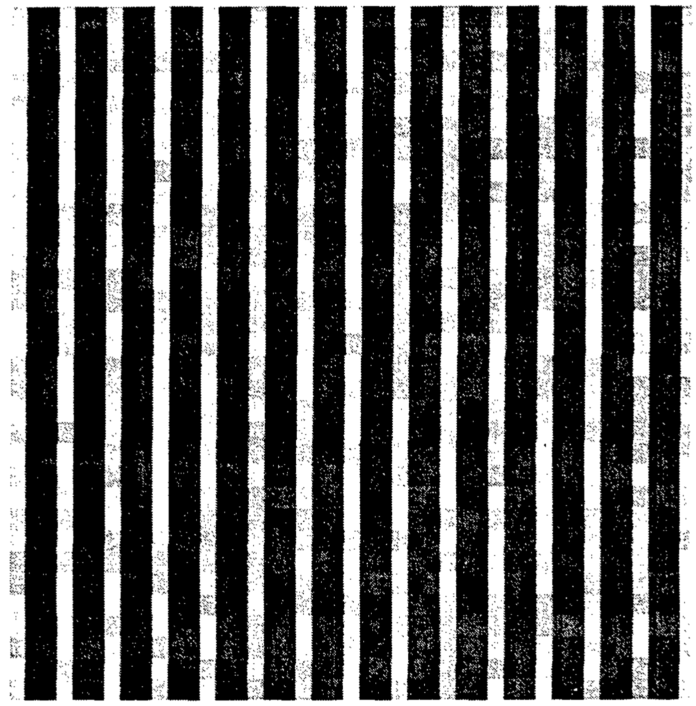


FIGURE 12



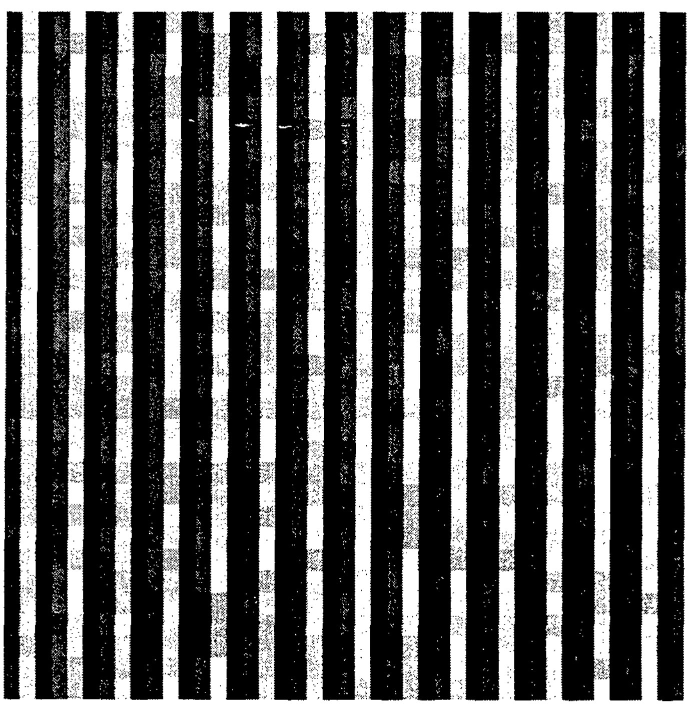
Linear Polarizer Analyzer at 0 degree orientation

(a)



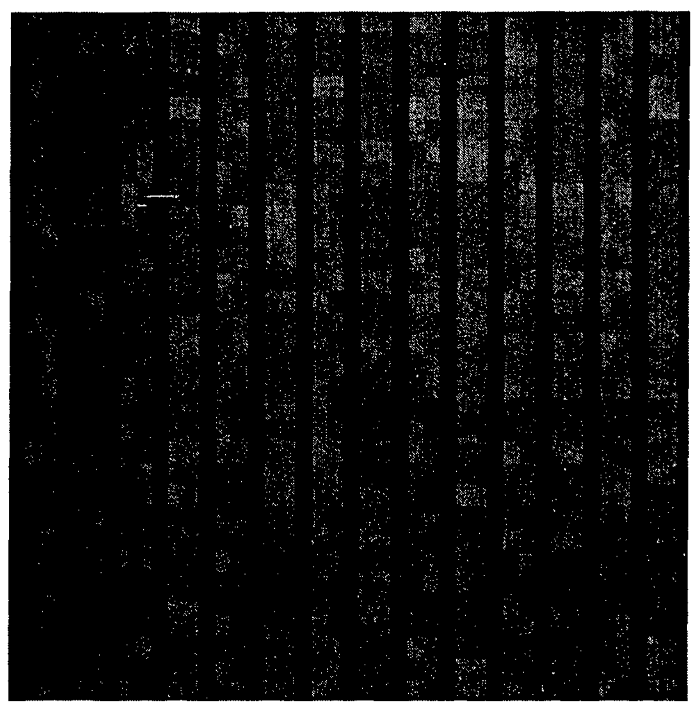
Linear Polarizer Analyzer at 45 degree orientation

(b)



Linear Polarizer Analyzer at 90 degree orientation

(c)



Linear Polarizer Analyzer at 135 degree orientation

(d)

Linear polarizer imaged at respectively 0, 45, 90, and 135 degrees using a photochip with deposited micropatterned polarization mask having adjacent polarization column. states of 0, 45, 90 degrees.

FIGURE 13

relative to the horizontal pixel scanlines. Individual pixels are clearly delineated in these images which clearly show the relative extinction of each of the polarization column states- observe a particular column in one of the images in Figure 13 and look at the corresponding column in the other images to see how this varies within the range of values bright grey, middle grey, and, dark. The spatially varying light pattern in Figure 13(a) is analagous to that in Figure 10 as both images are taken for the linear polarizer in front of the lens oriented at 0 degrees. When the linear polarizer in front of the lens is at 45 degrees to horizontal as for Figure 13 (b), the horizontal and vertical polarization column states are both at relative 45 degrees cross-polarization both producing a middle grey transmission while the 45 degree polarization column state produces a bright grey. When the linear polarizer in front of the lens is at 90 degrees to horizontal (i.e., vertical) as for Figure 13 (c), bright and dark grey transmissions are transposed with respect to Figure 13 (a), and the 45 degree polarization column state is middle grey. When the linear polarizer in front of the lens is at 135 degrees to horizontal (i.e., 45 degrees relative to horizontal but in the opposite direction as the 45 degree rotation), the 45 degree polarization column state is now extincted to dark with the 0 and 90 degree polarization column states both middle grey.

The *effective* extinction ratio of the portion of a polarization column state over a pixel (i.e., with respect to a micropatterned polarization mask deposited onto the imaging chip), can be measured by taking the ratio of the brightest grey value divided by the darkest grey value produced from different orientations of a linear polarizer in front of the camera lens. For the images in Figure 13 this particular subregion is near the edge of the image chip (i.e., "worse case") where light rays are incident at about 30 degrees relative to the surface normal of the chip. The average effective extinction ratio over the region of pixel photosites covered by the micropatterned polarization mask is 22.3:1, over twice as high as the 10:1 extinction ratio expected when the STTR Phase I effort was originally proposed. The worse case extinction ratio is slightly higher than 10:1. The lack of uniformity over some of the pixels (e.g., in a given column not all grey values are exactly the same) is due to a combination of the CCD photosensor noise together with the micropatterned mask not being perfectly flat along the surface of the image photochip.

5. SOME LOW-LEVEL TECHNICAL DETAILS OF DEVELOPMENT

The breakthroughs over the last year that facilitated the production of a thin high resolution micropatterned polarization mask involved the patterning and layering of an iodide doped liquid crystal material using photolithography and plasma etching techniques (NOTE: liquid crystal materials cover a broad range of materials and have a diverse range of properties- liquid crystal material discussed in this section is distinct from the discussion of twisted nematic liquid crystal cells discussed in section 1 - this material is completely passive). Most standard polarizing film is produced from a substance called Polyvinyl Alcohol (PVA) which linear polarizes light along the axis in which it is stressed or stretched. The thinnest such PVA polarizing film that is commercially available is 0.001 inch thick which translates to approximately 25 microns thick. From discussion in section 2, a single layer of this film is at least 5 times too thick, and since micropatterning could involve the stacking of more than one such polarization layer this makes using PVA even more problematic.

In the past year, Prof. David Brady and doctoral graduate student JunPeng Guo in the Department of Electrical and Computer Engineering, at the University of Illinois at Urbana-Champaign (under subcontract) have experimented with a number of different technologies for thin materials that polarize efficiently and that could be easily micropatterned. One of the technologies they have explored extensively is the use of wire grid polarizers which are more standardly used for polarizing light in the mid-infrared spectrum. While the wire grid technology can be made very thin, on the order of submicron thickness, the lines of conductive metal used for linear polarizing light at shorter visible wavelengths has to be made extremely thin on the order of 50 nanometers. Not only is this at the current edge of etching technology, but the physical properties of metals at this scale of thickness become altered in a way that needs to be understood further. For the moment wire-grid polarizing technology at visible wavelengths has been "put on the shelf".

The most definitive advance has been made by experimentation with a liquid crystal (LC) substance that can be made extremely thin (i.e., 0.3 microns thick) and that can serve as a substrate for aligning iodide molecules that efficiently polarize light in the direction of this alignment. A thin layer of this iodide-doped liquid crystal film was spin-coated onto the surface of a glass substrate after the surface was physically rubbed in a specific direction. The liquid crystal molecules

were aligned according to the physical rubbing direction, and the iodide molecules dispersed in the LC were aligned accordingly as the LC layer was dried. Since the iodide is responsible for linear polarization by dichroism, the effective polarization bandwidth is in the visible range from 400 nm to 700 nm. Dried LC polarization thin films with thickness between 0.3 to 0.5 microns were formed on the glass substrate. Figure 14 shows a transmission curve for light passing through this thin polarizing material in series with a linear polarizer at relative angular orientation denoted on the horizontal graph axis-- the ratio of maximum to minimum transmission (i.e.,extinction ratio) is about 100: 1.

The next step is to pattern the LC polarizing material into a mask to be used for a polarization imager. Patterning the LC polarizer film used photolithography and plasma etching techniques. E-beam lithography was used to make a chromium (Cr) mask which consisted of 16 micron opaque lines and 32 micron transparent lines, alternatively. Then UV photo-lithography was used to transfer an e-beam pattern on the mask to photoresist (PR) pattern on the dried LC film. The pattern was developed with both wet and dry processes. A selective reactive ion etching (RIE) approach was developed to effectively remove the UV-exposed LC film and left the PR pattern intact. These processes involved:

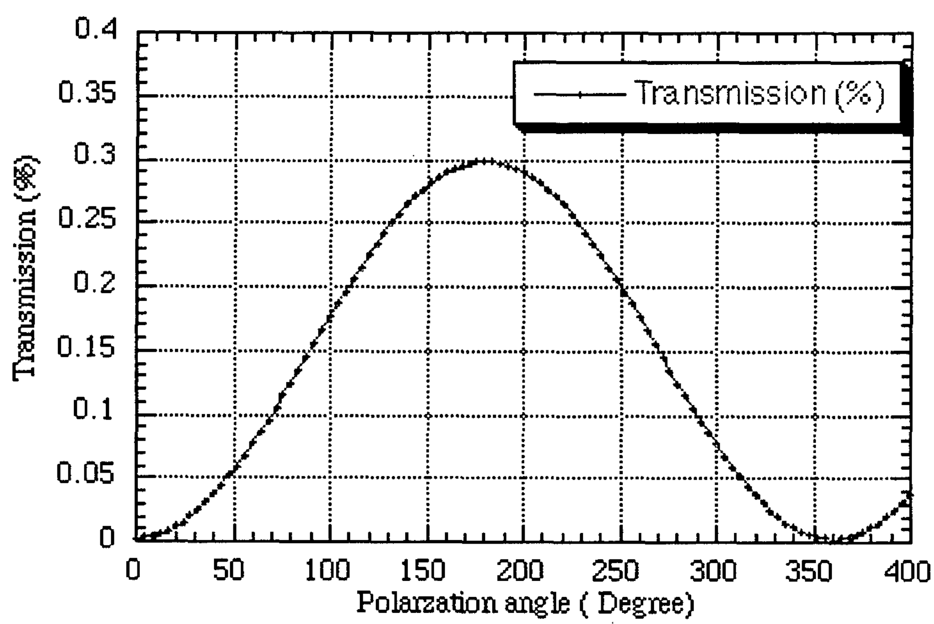


FIGURE 14

- Develop a recipe for the UV lithography--PR coating thickness, UV exposure time, soft baking temperature and time, and PR pattern development time. Since the LC film is dissolvable in most of PR developers which eventually undercut the PR pattern on it, a new method was developed to overcome this problem.

- Find the right plasma ions which can effectively etch away the developed part of LC film and also maintain the PR pattern on it. Because RIE etching is an anisotropic etching process, the PR pattern can be well copied to the LC polarizer film and there is minimal undercutting effect there.

The top illustration of Figure 15 shows a cross section of the resulting first layer of LC film (in Red) deposited onto the glass substrate (in Blue). Note that as the width of the Red rectangle is 16 microns and the height is 0.3 microns that in actuality the Red rectangles are much longer horizontally than vertically.

The next step is to stack a total of three alternating LC layers, the polarization axes at respectively 0, 45, and, 90 degrees, to make a 'three-state' mask. An approach was developed to make thin

Figure 5a. Cross section of the first state micro-polarizer patten on glass substrate

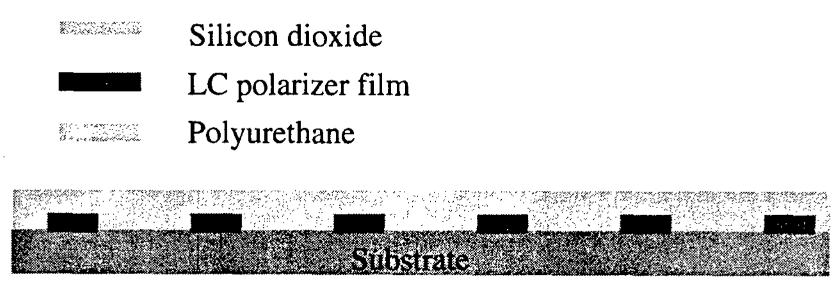


Figure 15

buffer layers between the successive LC polarization states. The bottom illustration of Figure 15 shows a cross section after a coating with a thin layer of polyurethane (1.5 micron) film which covers completely the first state device and then an evaporated thin layer (0.2 micron) of silicon dioxide (SiO2) on it to make the second state polarization film having same kind of sub-

Repeating the above processes to make the second state polarizer on top of the first state polarizer and the third state polarizer on the top of the second state polarizer yields a mask with cross section as in Figure 16 . The total thickness of this three state micro-polarizer is about 4.3 microns.

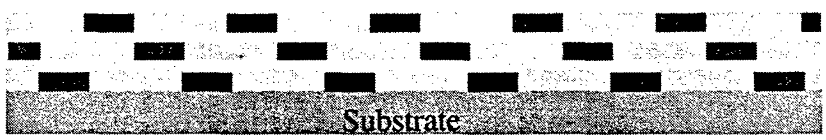


Figure 6. Cross section of the three state micro-polarizer.

FIGURE 16

6. CONCLUSION

The STTR Phase I effort this past year has resulted in a successful feasibility demonstration, producing a micropatterned polarization film with high extinction ratio, two orders of magnitude thinner and over one order of magnitude higher resolution detail than any previously existing. This mask was aligned on a CCD photochip using a nano-positioner such that periodic linear polarization states of 0, 45, and 90 degrees were precisely positioned over respectively adjacent single 16 micron wide pixel photosite columns producing an average effective extinction ratio of 22.3:1, over twice as high as expected at the beginning of Phase I. The imaging results of a linear polarizer at three successive orientations are shown in Figures 13 (a), (b), (c). A proposed Phase II STTR effort would transition the process of producing a micropatterned polarization mask, developed during Phase I, into directly adhering and precisely aligning the mask onto the photochip in a single operation. This is expected to result in an effective extinction ratio of at least 100:1. Integrating this polarization imager chip design into the Electrim EDC-1000 camera line will provide the first general purpose polarization imager. This could be run off a standard PC computer or further customized for specialized applications.

BIBLIOGRAPHY

[1] L.B. Wolff, "Polarization Methods in Computer Vision", Columbia University, January,1991

[2] L.B. Wolff, "Polarization-based Material Classification from Specular Reflection",IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI), November 1990, vol. 12, no. 11, pp. 1059-1071

[3] L.B. Wolff, "Applications of Polarization Camera Technology", IEEE EXPERT, Vol. 10, no. 5, pp. 30-38, October, 1995.

[4] L.B. Wolff and T.A. Mancini, "Liquid Crystal Polarization Camera", Proceedings of the IEEE Workshop on Applications of Computer Vision, December, 1992, pp.120-127, Palm Springs, California